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Michaels, C.F.; Zeinstra, E.; Oudejans, R.R.D.

published in
The Quarterly Journal of Experimental Psychology. Section A : Human experimental psychology
2001

document version
Peer reviewed version

THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY, 2001, *54A* (1), 69–93

Information and action in punching a falling ball

Claire F. Michaels, Edzard B. Zeinstra, and Raôul R.D. Oudejans

Vrije Universiteit, Amsterdam, The Netherlands

Lee, Young, Reddish, Lough, and Clayton (1983) reported that the timing control of jumping and vertically punching a dropping ball exploits the inverse of the rate of change of optical expansion, $\tau(r)$. We raise a number of methodological and logical criticisms against their experiment and conclusions and attempt to rectify them by examining elbow joint angles only, in seated punchers, under both monocular and binocular conditions, with two ball sizes, dropped from two heights. Differences between the binocular and monocular cases suggest the exploitation of different information. We present several techniques to help determine the operative variable(s) controlling the action. The optical variable used to initiate and guide flexion appeared to be expansion velocity (looming), rather than $\tau(r)$; extension appeared to be under the control of different variables in the monocular and binocular cases. Simulations using single variables and single perceptuo-motor intervals were of mixed success.

The concept $\tau(r)$, once known simply as τ (e.g., Lee, 1976),[1] the ratio of image size (r) to expansion velocity, ($\dot{r}$), specifies the time-to-contact between an eye and an approaching object, given certain boundary conditions. One boundary condition is that the object approaches at a constant velocity; $\tau(r)$ overestimates time-to-contact when the velocity between eye and object increases- say, when the eye of a gannet accelerates toward the water, or when a ball falls toward a would-be puncher's eye. Perfect timing of a time-to-contact related action would require that acceleration be perceived (or taken into

[1] The more general dictionary of tau concepts presented by Lee and his colleagues (e.g., Lee, Young, & Rewt, 1992) is adopted here. The concept $\tau(x)$ is defined as a generic tau function- the ratio of a scalar variable x to its rate of change ($\dot{x}$). Thus, we use τ to capture all such variables. In referring to the inverse of the rate of optical expansion, we prefer to use planar image diameter (r), rather than solid angle, as employed by many (e.g., Tresilian, 1990), given our demonstrations that time-to-contact judgements do not reflect relative rate of change of area (or solid angles), but relative rate of change of linear dimensions (or plane angles; Oudejans, Michaels, & de Vries, 1993a, b).

Requests for reprints should be sent to Claire Michaels, Faculty of Human Movement Sciences, Vrije Universiteit, van der Boechorststraat 9, 1081 BT Amsterdam, The Netherlands.
Email: C_F_Michaels@FBW. VU.NL

We thank Nicolette van Dikkenburg, Bert Coolen, and Maaike Pronk for help in analysing the data and Patrick Haggard, John Wann, and Frank Zaal for comments on a draft. An earlier version of this paper was presented at the 9th International Conference on Perception and Action, Toronto, July, 1997.

http://www.tandf.co.uk/journals/pp/02724987.html DOI:10.1080/02724980042000039

account), but Lee, Young, Reddish, Lough, and Clayton (1983) have proposed that a first-order strategy- using $\tau(r)$ irrespective of conditions of acceleration- would lead to reasonably successful timing in most situations. They termed this a tau-margin strategy.

Lee et al. (1983) explored the timing of interceptive action under conditions of acceleration, and their article has had a substantial impact on the perception–action community. Participants were asked to jump to punch falling balls. Knee angles and elbow angles were recorded, along with the times of ball release and fist–ball contact. The usage of the tau-margin strategy entailed two predictions: (1) Elements of the action should begin earlier for balls dropped from greater heights, because a ball dropped from a greater height will reach $\tau(r)$ values at a longer time-to-contact than balls dropped from lesser heights (see Figure 1); and (2) the differences among punches of balls dropped from different heights should decrease as the ball approaches, because the value of $\tau(r)$ for the various heights converge (on time-to-contact, again, see Figure 1).

In support of the tau-margin hypothesis, Lee et al. (1983) showed that average joint angles plotted against $\tau(r)$ showed the predicted convergence and that plots of joint-angle trajectories in response to balls dropped from different heights were more similar when plotted against $\tau(r)$ than when plotted against time-to-contact.

The Lee et al. (1983) study is not without its critics. Tresilian (1993) has argued that the results concerning the timing of the beginning of the action could also be accounted for in terms of initiating the action in response to ball release; flexion occurring just after the drop would yield results similar to a tau-margin strategy. Furthermore, Wann (1996) has argued that, in general, the apparent convergence of joint-angle trajectories when plotted against $\tau(r)$ for different heights can be an artifact of the nonlinear compression of the abscissa and that other similar compressions, unrelated to $\tau(r)$, would also yield convergence.

In this article, we take issue with other aspects of Lee et al.'s (1983) methods as they bear on permitting inferences about the relation between the unfolding action and $\tau(r)$ (or *any* optical variable). First, to determine the (succession of) values of optical variables, the

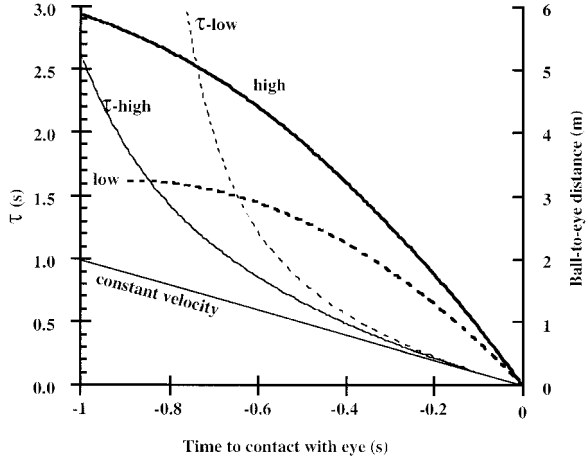


Figure 1. Distances to the eye (bold face), referenced to the right ordinate, and τ values, referenced to the left ordinate, for balls dropped from the two heights employed in the present experiment, given as a function of time-to-contact with the eye.

distance from eye to ball must be known. This was not the case in the Lee et al. study for two reasons. The estimates of the values of eye-ball distance over time assumed that the observation point was stationary; this was not the case because eye height dropped as the knee flexed and rose as the knee extended. In addition, the estimates of eye–ball distance were not based on known ball positions, which were not recorded, but on idealized trajectories that assumed an acceleration of 9.8 m/s^2- that is, an acceleration that ignores drag effects.

A second set of problems concerns how the joint-angle trajectories were determined. The procedure used to average joint angles could obscure the very differences of interest. To average over trials, the successions of joint angles were temporally aligned *with moment of fist–ball contact* and then averaged. It strikes us that if one ultimately wants to examine joint angles as a function of an optical variable, one should not average over possibly different values of the optical variable. This would have been the case if ball–fist contact were not made at precisely the same time or place, relative to eye contact, on every trial. Another troublesome issue with the joint angles is that Lee et al. (1983) normalized joint angles trial by trial and over punchers. The rationale for this was an expressed interest only in the *timing* of the punch. However, normalizing washes out real (as opposed to relative) joint-angle velocity, which amounts to assuming that (changing) movement velocity is not part of timing.

The goal of the present article is to re-examine the punching of falling balls using an experiment that remedies these problems. Punchers were seated and ball trajectories videotaped, so optical variables could be determined directly from known eye and ball positions. Our working hypothesis is that $\tau(r)$ provides the information that guides punching. The predictions entailed by the use of $\tau(r)$ depend, in part, on the control law (Kugler & Turvey, 1987; Warren, 1988) that is hypothesized to relate the optical variable to the creation of forces. However, $\tau(r)$-based control laws (continuous control, discrete triggering of invariant ballistic movements, or parameter setting followed by triggering of ballistic movements) have a few predictions in common; see Tresilian (1993), for a discussion of control strategies related to the possible use of $\tau(r)$. First, there are quantitative predictions about the timing of punches of balls dropped from different heights. Consider the example described in Figure 1: If (a part of) the action, A, were initiated at some $\tau(r)$ value, say 2 s, one would expect A to begin some 200 ms earlier for a high ball than for a low ball. If A were initiated at a $\tau(r)$ value of 0.5 s, the difference in A to high and low balls would be only about 20 ms. Second, the use of $\tau(r)$ predicts that neither different ball sizes nor viewing conditions (monocular vs. binocular) should influence the timing of the punch. With respect to the size prediction, there is empirical evidence to suggest that, at least in simulations, size does affect time-to-contact judgements (e.g., DeLucia, 1991; DeLucia & Warren, 1994; Oudejans, Michaels, & de Vries, 1993a, b). There is also evidence that leads to the expectation of differences as a function of viewing condition; several studies have reported differences in interception based on viewing conditions (Heuer, 1993; Judge & Bradford, 1988; van der Kamp, Savelsbergh, & Smeets, 1997). In addition, binocular variants of τ, not related to image size, have recently been derived (e.g., Gray & Regan, 1998; Laurent, Montagne, & Durey, 1996).

The various problems with the Lee et al. (1983) experiment together with the various discoveries enumerated here suggest that it is time to have another look at the punching of falling balls.

EXPERIMENT

Method

Participants

Five males participated in the experiment. Their average age was 25 years (range 23–30 years). All reported normal or corrected-to-normal vision.

Design

The experiment consisted of two blocks of 40 trials. In one block, vision was binocular; in the other, it was monocular, with the non-dominant eye occluded by an eye patch. Three participants began with the monocular block, and two began with the binocular block. In each block, participants were tested in four conditions: the combination of two heights from which the balls were dropped, 7 and 5 m above the ground, and two ball sizes, diameters of 25.8 and 20.7 cm. The durations of the drops to eye level (1.27–1.30 m above the floor) were approximately 1.3 and 0.9 s for the drops from 7 and 5 m, respectively. On each trial, one of the two balls was dropped vertically from one of the two heights. The task of the participant was to punch the dropped ball as hard as possible straight up in the air. Within blocks of viewing condition, drop types (higher/lower, bigger ball/smaller ball) were randomized in a different order for each participant.

Experimental setup

The experiment is schematized in Figure 2. It was executed in a gym-sized lab (height 7 m) where the balls were suspended from the ceiling with a light, monofilament fishing line attached to a spinning reel. When the bail of the reel was open, the ball fell freely toward the puncher's eye.

The participant was seated on a chair directly under the to-be-dropped ball with his punching arm extended downward in a relaxed posture at his side. The punch began with an elbow flexion that brought the forearm to near vertical (see Figure 2). This was followed by a shoulder and elbow

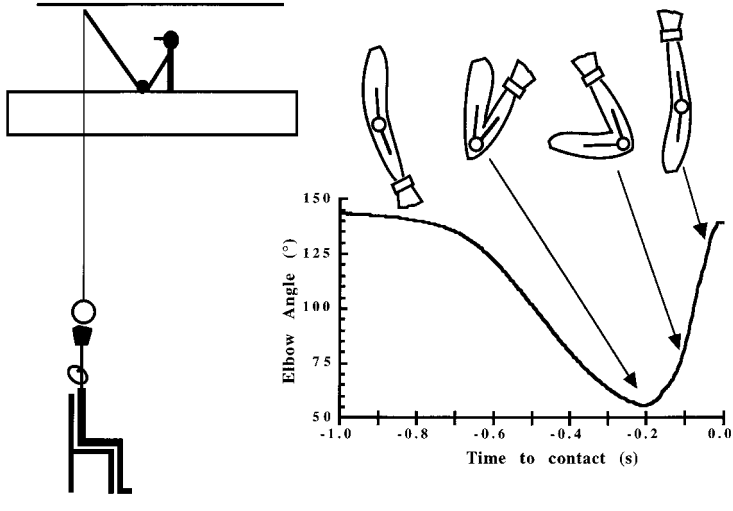


Figure 2. Left: Schematic of the experimental setup. Balls were dropped from directly above the puncher's head. Right: At the time of ball release, the arm is extended loosely at the side. The elbow is flexed and then extended; a sample trace of elbow angle as measured by the goniometer is shown.

extension, in which the forearm remained near vertical. The elbow angle of the punching arm was registered by a goniometer and was sampled by computer at a rate of 200 Hz. A major part of each ball trajectory was videotaped at 50 Hz with a Panasonic camera connected to an S-VHS Blaupunkt video recorder. An Alpermann & Velte Time Code 30 generator wrote a Vertical Interval Time Code (VIT code, a unique time code) on the videotapes. On each trial, there was a light flash visible on video every time the goniometer started registration. As a result, video and goniometer data could be linked in time to a 20-ms accuracy.

Procedure

The goniometer was attached, and, in the monocular case, the eye patch was donned, and the participant was seated as shown in Figure 2. In order to minimize punchers' knowledge of which condition (high/low, big/small) would come next, they were instructed to look up only after the signal from the experimenter, just before the next ball was dropped. The puncher looked up, and the ball was dropped and punched. The ball was then reeled in, replaced if necessary by the other ball, and lowered to the proper height for the next trial. There was a short break between the two blocks of trials, and the entire experiment lasted about one hour.

Digitization

The ball trajectories were digitized from the videotapes. Equations for ball trajectories were determined by fitting a second-order polynomial to digitized position data, so that optical variables could be continuously computed and thus not be subject to variability in frame-to-frame digitization or limited to the temporal resolution of the video.

The exact height and time of the punch were determined by plotting the vertical coordinates of the ball as a function of time and fitting the falling and rising trajectories separately. The intersection of the resulting equations was taken as the time and place of fist–ball contact. In this way, we were able to go beyond the 20-ms resolution of the videotape in localizing the punch in time and space. The downward trajectory of the ball was extrapolated to eye level according to the polynomial fit; the time of intersection of ball and eye plane was defined as time $= 0$.

Results and discussion

We divide our presentation of results into three parts. First, we briefly examine group tendencies in the timing of several discrete measures of the action, wherein we make some qualitative inferences about the optical control of the movement. Attention is then turned to the individual participants' continuous joint-angle trajectories, when we examine the averages of joint-angle trajectories within punchers and the individual trials within punchers. In the final section, we consider how to model the action.

Group tendencies: Discrete events

The time-to-eye contact of elbow-flexion onset and elbow-extension onset were determined for each punch. Three-way, within-subjects analyses of variance (ANOVAs) were used to determine whether the times of these events differed as a function of viewing condition (monocular vs. binocular), ball size (large vs. small), and drop height (high vs. low). The expectation was that if $\tau(r)$ was the operative variable, no effects would be observed for either viewing condition or size.

The onset of elbow flexion (elbow angle velocity > 0) differed as a function of the height of the drop, $F(1, 4) = 16.30$, $p = .016$. Flexion began earlier for balls dropped from 7 m (670 ms) than for balls dropped from 5 m (554 ms). There were no differences as a function of ball size or viewing condition and no interactions. As to whether the height effect implies that flexions are geared to $\tau(r)$ or geared to the release of the ball- the issue raised by Tresilian (1993)- the observed difference of 116 ms does not fit well with either prediction. The release times of the ball differed by about 0.4 s, whereas the approximate time-to-contact at which $\tau(r)$s differ by only 116 ms does not occur until much later, at a time-to-contact of less than 0.5 s (cf. Figure 1), well after the flexions are initiated.

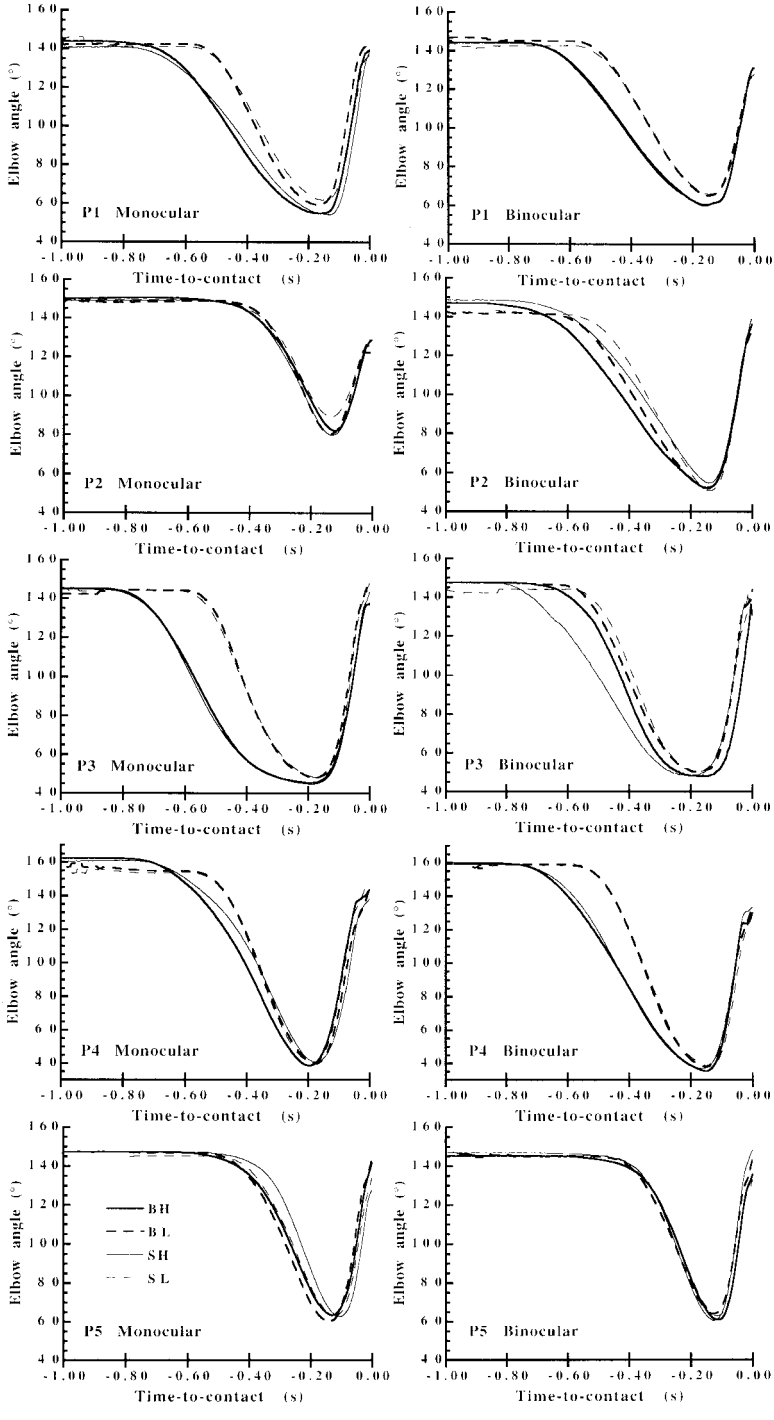
Extension onset was defined as the time at which the angular velocity of the elbow extension surpassed 100°/s. This stringent requirement was enforced to ignore small changes or drifting of the joint angle in the interval before extension. Only one effect, the interaction between viewing condition and size, was significant, $F(1, 4) = 10.64$, $p = .031$. Extensions began at the same time for large and small balls in the binocular condition (117 ms and 116 ms, respectively), whereas in the monocular case, extension to the large ball (129 ms) was earlier than that to the small ball (119 ms). Two other sources were marginally significant: the main effect of size (understandable in terms of the previous interaction) and the viewing-condition-by-height interaction, $F(1, 4) = 4.92$, $p = .09$, where the binocular case was again indifferent to drop height (at 117 ms), and the monocular case tended to show an earlier extension to low balls (127 ms) than to high balls (121 ms).

To summarize, flexion onset showed a 116-ms dependence on drop height; neither release-time differences (0.4 s) nor $\tau(r)$ differences (150 to 300 ms, depending on the assumed time taken to initiate flexion following the reaching of some value of τ) were implicated. The extension phase distinguished between the monocular and binocular cases, not as main effects, but in terms of variables that had effects in one condition but not the other. This suggests that different optical variables were exploited in the monocular and binocular cases. That ball size showed a significant effect on timing in the monocular case militates against the use of $\tau(r)$, at least in that case. The lack of difference between extension-onset times for high and low balls also rules out Wann's (1996) zeta, suggested as an alternative to τ. The use of zeta ($r_t/r_{t=0}$) predicts extension-onset differences of the order of 30 ms; with the ball sizes used here, a strategy based on zeta would be essentially the same as a strategy based on distance (see Figure 1).

Individuals' joint-angle trajectories

For each participant, the successions of elbow angles in time were aligned with respect to when the ball would have contacted the eye. These angles were averaged over trials for each drop type. Figure 3 presents these averaged elbow angles plotted as a function of

Figure 3. (Opposite.) Elbow angles for each drop type, averaged over trials, and given as a function of time-to-contact with the eye for the 5 participants. The left panels present the monocular cases; the right panels present the binocular cases. BH is the bigger ball dropped from the higher release point; SL is the smaller ball dropped from the lower release point, etc.


P1 Monocular
P1 Binocular
P2 Monocular
P2 Binocular
P3 Monocular
P3 Binocular
P4 Monocular
P4 Binocular
P5 Monocular
P5 Binocular
BH
BL
SH
SL
Elbow angle (°)
Time-to-contact (s)
160
140
120
100
80
60
40
-1.00
-0.80
-0.60
-0.40
-0.20
0.00

time-to-eye-contact.[2] As stated in the Method section, the drops lasted approximately 1.3 and 0.9 s from release to eye contact for the high and low conditions, respectively. In general, we see that flexion began considerably after ball release (0.5 to 0.8 s) and could be fairly protracted; extension began 100–200 ms before eye contact and tended to be faster than flexion. Fist–ball contact occurred 45 ms, on average, before the ball would have reached eye level. In what follows, we work our way through the trajectories, attempting to identify the optical information that was exploited.

Flexion onset. The elbow angle trajectories of most of the punchers showed an obvious effect of drop height- punches to high balls were initiated earlier than punches to the low balls. Exceptions include the monocular condition for Puncher 2 and both monocular and binocular conditions of Puncher 5. For the other conditions and punchers, the height effects on flexion initiation were qualitatively what one would expect based on a τ strategy, where Puncher 3's monocular condition and Punchers 1 and 4's binocular conditions were paradigmatic (i.e., showed no effect of ball size).

However, as intimated in the previous section, the τ hypothesis is undermined by the apparent existence of size effects in a number of the graphs presented in Figure 3. These include the monocular conditions of Punchers 1, 4, and 5 and the binocular condition of Puncher 2 (we ignore the binocular condition of Puncher 3 for reasons given in Footnote 2). However, among these four graphs, there is no obvious consistent pattern; the orders of flexion initiation to the bigger (B) and smaller (S), higher (H) and lower (L) drop types differ among participants. Puncher 1 showed the order BH SH BL SL (e.g., the order in which the four trajectories pass through an elbow angle of 100°); Puncher 2 showed BH BL SH SL; Puncher 4 showed BH SH BL=SL; and Puncher 5 showed the order, BL BH SL SH.

Three kinds of explanation come to mind for the different orders of flexion initiation. First, they could have been noise; however, ANOVAs revealed that they were not.[3] Second, it could have been that different observers exploited different optical variables in the control of the activity- for example, one puncher might have used τ to initiate flexion, yielding a BH=SH BL=SL pattern (see Figure 1), and another might have used a criterial image size, r, which with the current values of ball size and drop height would yield a BL SL BH SH pattern. The third possibility is that all observers used the same variable, but that that variable reaches different criterial values in a different order. Even though the last alternative may sound cryptic, it is quite simple and, as we shall see, appears to be the correct explanation; a single optical variable, $\dot{r}$ (optical expansion velocity) predicts all of the observed qualitative patterns.

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[2] The joint-angle data for the binocular case of Puncher 3 had extraneous noise bursts on all but two trials for each drop type, so the averages in that condition are based on only two trials. In all other cases, there were 8–10 usable trials per condition.

[3] Analyses of variance on the discrete events identified in the previous section were also carried out on the data of individual punchers. A crude measure of the order effects at issue in the current analysis is flexion onset time. All punchers showed a significant main effect of size or height (or both) in both monocular and binocular conditions, with the exception that Puncher 2's monocular condition showed only a marginally significant effect, $F(1, 28) = 3.56$, $p = .07$. Even Puncher 5, whose binocular conditions appear virtually overlapping in Figure 3, had significant size, height, and size-by-height effects: $F(1, 33) = 5.25$, $p = .028$; $F(1, 33) = 5.13$, $p = .030$; and $F(1, 33) = 4.80$, $p = .036$, respectively.

Figure 4 is a graph of $\dot{r}$ as a function of time-to-contact for the four drops. An interesting feature is that the curves cross (something that is not true of r, $\tau(r)$, or even $\ddot{r}$- the second derivative of r). If punchers were to use a criterial value of $\dot{r}$ to initiate the flexion, a number of consequences would follow. First, the relative order of initiation ought to depend on the criterial value used. Punchers that use a low criterial value of $\dot{r}$ (e.g., 0.002) would flex relatively early and demonstrate a BH=SH BL=SL ordering, the order in which $\dot{r}$ reaches the criterion for the four drops. (Note that only a negligible size effect is expected in that case.) Punchers that begin somewhat later, in accordance with a criterial value of 0.01, say, should show a BH SH BL SL ordering of onsets. A late initiation goes together with a higher criterial value of $\dot{r}$ (e.g., 0.04); punchers using this criterion should demonstrate a BL BH SL SH ordering, because that is the order in which the drops reach 0.05. Intermediate initiations could yield other orders.

The observed flexion-initiation orders were all to be expected on the basis of the usage of $\dot{r}$. For the monocular case, Puncher 3 showed a flexion pattern consistent with a very low criterial value; Punchers 1 and 4 showed patterns consistent with a slightly larger criterial value of $\dot{r}$; and Puncher 5, who moved the fastest and who initiated flexion considerably later than the other punchers, showed the ordering that would be expected with a higher criterial value of $\dot{r}$. Similar patterns were found in the binocular version, except for Puncher 5 whose average flexions (and extensions) overlapped for the four drop types.

Let us now attempt to push this qualitative agreement between $\dot{r}$ and flexion into a quantitative one. There are two barriers to this; for any given graph in Figure 3, we know neither the criterial value of $\dot{r}$, nor the delay between when $\dot{r}$ reaches that criterial value and when the movement begins. One cannot expect the $\dot{r}$s at flexion onset to be the same;

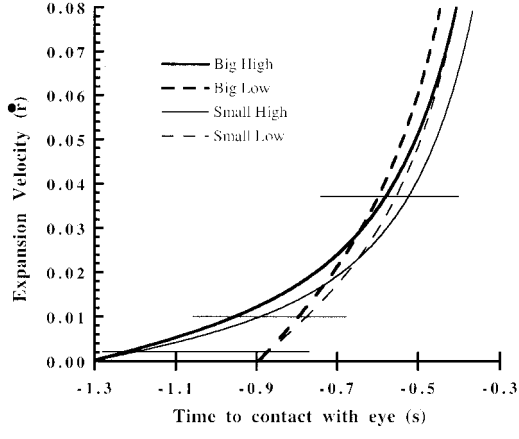

Figure 4. The first derivative of image size, $\dot{r}$, plotted for each of the size–height combinations used in the experiment and given as a function of time-to-contact. The horizontal line segments depict the criterial values of $\dot{r}$ mentioned in the text; these criteria would yield the different ordering of flexions observed among the punchers.

they would only be the same at a point in the past equal to the action initiation interval.[4] We tackle this problem as follows: On the basis of known ball sizes and trajectories, we can compute where the ball was and how fast it was moving and, thus, the values of $\dot{r}$ (or other optical variables) at the moment flexion began on each individual trial. We can repeat the procedure for particular intervals before flexion onset (e.g., 50 or 100 ms). If $\dot{r}$, say, is, the variable on the basis of which flexion is controlled, then it ought to be the case that the values of $\dot{r}$ converge on some value at some previous point in time. Examples of such an analysis are given in Figure 5.

Figure 5 is read as follows, beginning with the binocular case given in the lower panel: At the moment of flexion onset (0.0 on the abscissa) the values of $\dot{r}$ for the four drop types (shown by the open symbols) are very different, ranging from about 0.042 to about 0.018. However, as we look to the right, further back in time, to see what the four values of $\dot{r}$ were at various intervals before flexion onset, we see that the curves converge at around 250 ms, at an $\dot{r}$ value of approximately 0.01. The upper panel of Figure 5 looks somewhat different, but the general trend is the same- again, $\dot{r}$s at flexion onset were very different, and again we see convergence as we look back in time. However, in this case the convergence is somewhat later, around 200 ms, and the convergence is at a different point, on the order of 0.02, an $\dot{r}$ value that occurs later in the trajectory of the drop. The differences between the converged-upon values are also reflected in the different flexion-onset times for these two punchers, as seen in Figure 3. Puncher 5's monocular case is initiated some 150 ms later than Puncher 4's binocular case.

One can also do ANOVAs on the values of the computed optical variables at each of the points in time. The p values yielded by one-way ANOVAs testing the effect of drop type on $\dot{r}$s at that interval are plotted as the solid circles in Figure 5. We can use these p values as an informal test of how different the average values of the optical variables were. For the upper graph there were no significant differences ($p < .05$) at any interval except 300 ms, where there appears to be a marginal effect. For the lower panel, the drop types differed significantly for all intervals tested *except* 225 and 250 ms. Such analyses nominally test the null hypothesis that the variable in question could have been operative at that interval. If the effect is significant, then the values of said variable at the specified interval prior to flexion onset were statistically different and, thus, could not have provided the common basis for initiating the action. In the case of the lower panel of Figure 5, then, the ANOVAs reveal that $\dot{r}$ at an interval of 225 or 250 ms cannot be rejected as a possible optical basis for flexion initiation, though other intervals can be.

A few additional remarks about Figure 5 are in order. First, most of the graphs (both monocular and binocular- even that of Puncher 5) looked more like the lower panel than the upper one in terms of the error variance. In the upper panel there is an obvious lack of statistical power in rejecting the null hypothesis that, for example, $\dot{r}$ at an interval of 25 ms

[4] We have tried to avoid the terms *reaction time*, *perceptual-motor delay*, etc. and use the more neutral *interval*. Much of the measurement of intervals between stimulus events and movements has traditionally emphasized minimal intervals or otherwise implied that intervals are of a some fixed magnitude. Although we do not deny that rates of neural conductance set certain lower limits, we believe that the interval over which any control law operates is an empirical question, and we anticipate that such intervals can take on many values depending on whether attention is already directed to the information that will guide the action, the nature of that information, the time it takes to assemble the action, and the inertia of the elements that must be accelerated, as well as a host of time-biding intentions.

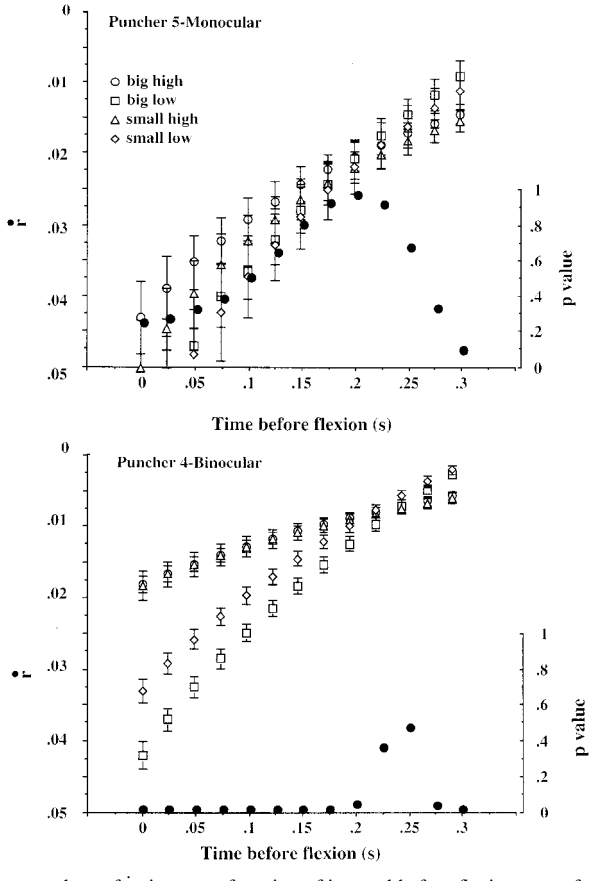

Figure 5. The average values of ṙ given as a function of interval before flexion onset for each of the four drop types (indicated by the open shapes and bracketed with bars indicating standard errors). Upper panel: Puncher 5 in the monocular condition. Lower panel: Puncher 4 in the binocular condition. The solid circles indicate the *p* value of a one-way ANOVA testing whether there was a significant difference among the drop types at that interval. These probabilities are referenced to the right ordinate. See text for explanation.

is used.[5] However, the changing pattern of probabilities still gives a good impression of a likely interval between the appearance of a critical ṙ value and when the movement begins.

Table 1 presents the values of ṙ and temporal intervals for which the *p* values were the highest for the remaining cells (to the nearest 25 ms). Similar analyses were carried out on other optical and physical variables that might have served as information for initiating flexion (momentary distance to the ball, momentary ball velocity, r, and τ); none of these other variables showed convergence.

[5] The difference in variability between the upper and lower panels of Figure 5 is not due to differences in timing variability between the two punchers (which can be seen if we look ahead to Figure 6), but to the different initiation times. Puncher 5 initiated his flexions later than did Puncher 4– at a time where ṙ was changing much more rapidly.

TABLE 1
The combination of values of $\dot{r}$ and the temporal interval back in time that yielded the highest probability

	Monocular		*Binocular*	
Puncher	$\dot{r}$	*Interval (ms)*	$\dot{r}$	*Interval (ms)*
1	0.009	225	0.009	225
2	0.017	275	0.015	150
3	0.007	225	–	–
4	0.010	225	0.007	250
5	0.021	200	0.018	225

The error bars in Figure 5 give some impression of the variability in flexion onsets within drop type; a more complete picture is given in the plots of individual trials in Figure 6. There is much to remark about Figure 6, but for now let us note simply that within condition and drop type there was considerable variability in onset times, except for the binocular condition of Puncher 5. Thus, the "criterial" values of $\dot{r}$ that we hypothesized in the previous paragraphs are not to be considered as values to which the onset of flexion is tightly tuned. The fact is that the task demands permit one to flex at a leisurely pace without jeopardizing the timing of the punch. Given the drop heights that were used, there is no demand for low-variability flexion onsets. It appears, however, that one action style- Puncher 5's more ballistic and late-starting combination of flexion–extension- may have demanded low variability.

Rate of flexion. The ability of $\dot{r}$ to predict the orders and (average) differences in flexion onset to the different drop types is only part of the story of the optical control of flexion; there were also differences in rates of flexion as can be seen in both Figures 3 and 6. In general, the less time that is left until ball–eye contact, the faster the flexion. To test whether these slope differences were statistically reliable, we measured the slope (angular velocity) of a particular slice of flexion, from 120° to 110°, on each trial. A total of 10 two-way ANOVAs (five punchers by two viewing conditions) showed that these slopes differed significantly among drop types in most cases. Exceptions were the noisy data of Puncher 2 and the sparse data of Puncher 3's binocular case; additionally, the binocular case of Puncher 5 showed only a marginally significant effect of height, $F(1, 33) = 3.29$, $p = .079$.

To examine which candidate optical variables best predicted the rate of flexion, we computed correlation coefficients between the flexion slopes and the values of $\dot{r}$, $\ddot{r}$, time-to-contact, τ and $\dot{\tau}$ at various points in time prior to the slice. This analysis is analogous to that in the previous section; the correlations between slope and the utilized variable should be higher than the correlations between slope and other variables, and the correlations should be highest at the operative interval. Significant correlations were found with one or more optical variables at one or more intervals for all punchers in both conditions.

Figure 6. (Opposite.) Raw joint-angle trajectories for (the first) five trials in each condition for each puncher. The binocular condition of Puncher 3, for which we had only eight useable full trajectories, is plotted in full.

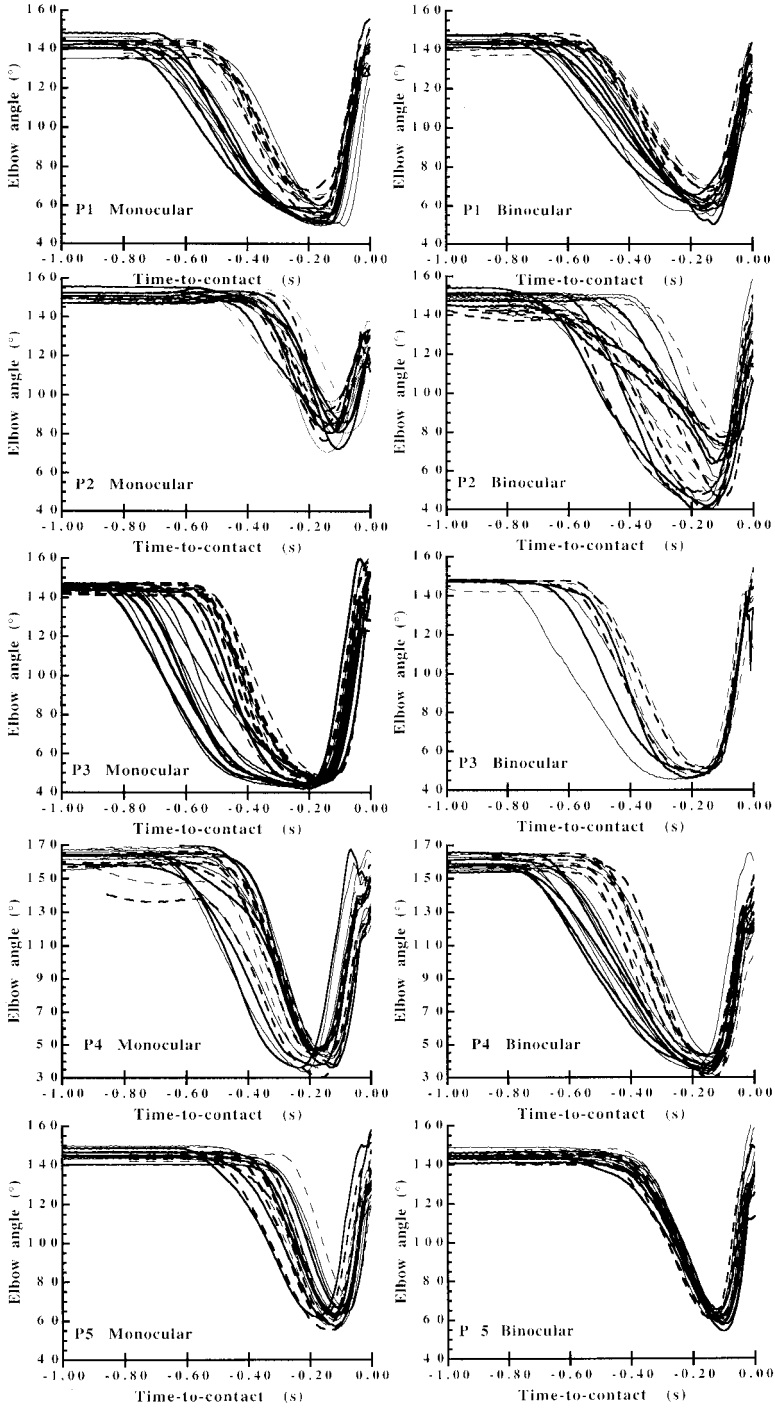
P1 Monocular
P1 Binocular
P2 Monocular
P2 Binocular
P3 Monocular
P3 Binocular
P4 Monocular
P4 Binocular
P5 Monocular
P 5 Binocular
Elbow angle (°)
Time-to-contact (s)

TABLE 2
Highest observed correlations between flexion velocity and optical variables given by condition and puncher

Puncher	*Monocular*	*Binocular*
1	.626	.755
2	.571	.428
3	.638	.645
4	.813	.854
5	.714	.826

Unfortunately, the predictor variables were so highly correlated with their temporal neighbours and with each other that no firm conclusions could be drawn about which variables or which intervals were best. Thus, Table 2 presents only the highest correlations without naming variables or intervals.

The correlations in Table 2 are not due exclusively to differences among drop types. Correlations between optical variables and flexion velocity were also computed *within* drop type, and these correlations were comparable to those presented. Thus, later-starting flexions within one drop type had a higher velocity than earlier-starting flexions to the same drop type. For example, in Puncher 4's binocular condition in Figure 6, flexions to the small high balls (the thin solid lines) began over a range of 200 ms and the later-starting of these have steeper slopes, leading to a convergence of the joint angles at around −200 ms. One can conclude, therefore, that the exploited optical variable- whatever it may have been- did not simply trigger a stereotyped action in some temporally noisy way, but that its particular value when the action starts (or perhaps even as it unfolds) parameterizes (or perhaps continuously guides) the flexion.

To summarize, the elbow-flexion rates of all punchers are accommodated to the time remaining before eye contact: the less time remaining, the faster the flexion.[6] Because flexion was sometimes initiated over a large range of intervals and because all optical variables were changing over those intervals, we could not determine which particular optical variable was used to control flexion rate, or how it did so. Any of a number of variables and control laws could yield the observed pattern: Flexions could be parameterized by any of several variables (r, $\dot{r}$, $\ddot{r}$, or τ) and run off ballistically, or they could follow one of these variables (e.g., the faster $\dot{r}$ changes, the faster elbow angle changes) by virtue of being continuously or intermittently coupled to it.

Initiation of extension. Figures 3 and 6 make clear that the extension phase of the action is more tightly coupled to the arrival of the ball than is the flexion phase. The trajectories for the four drop types converge into a narrow bundle, with the binocular condition appearing to be more finely tuned than the monocular condition. The average extension-onset times for individual punchers and conditions are presented in Table 3.

[6] The trajectories of Puncher 5 may suggest a ballistic pattern, but Table 2 reveals that there are systematic slope variations. Thus, if the punch of Participant 5 is organized as a whole, then it is parameterized.

TABLE 3
Average extension onset times[a] and significant drop-type effects for all punchers and viewing conditions

	Monocular					*Binocular*				
	BH	*BL*	*SH*	*SL*	*Sig?*	*BH*	*BL*	*SH*	*SL*	*Sig?*
1	−0.127	−0.131	−0.116	−0.115	–	−0.118	−0.106	−0.107	−0.106	–
2	−0.100	−0.119	−0.102	−0.105	–	−0.116	−0.119	−0.119	−0.117	–
3	−0.129	−0.135	−0.129	−0.132	–	−0.123	−0.131	−0.125	−0.135	–
4	−0.161	−0.146	−0.142	−0.153	–	−0.131	−0.128	−0.133	−0.120	–
5	−0.107	−0.119	−0.088	−0.107	S, H	−0.099	−0.109	−0.110	−0.096	S × H
All	−0.125	−0.131	−0.116	−0.122	S	−0.116	−0.117	−0.118	−0.115	–

[a] Extension onset times are given in s.

Individual ANOVAs compared the four drop types within punchers and viewing condition. The results, which are also presented in Table 3, show that only Puncher 5 had significant differences in extension onset time to the four drop types.

As to the possible optical basis of extension initiation, we can interpret the non-significance of differences in the observed time-to-contact of extension initiation as we did non-significant differences in Figure 5. Doing so, we would conclude that optical variables specifying time-to-contact, *ttc* (e.g., a variable that takes acceleration into account, such as that derived in Lee et al.'s, 1983, Appendix A) cannot be eliminated as a possible basis for the onset of extension in the monocular and binocular conditions of Punchers 1–4; though it can in the case of Puncher 5. Note that one cannot, in the case of (variables specifying) time-to-contact, determine the "optimal interval"; going back in time subtracts the same amount for each drop type, leaving the significance tests unchanged.

We asked whether optical variables other than those specifying time-to-contact *can* be eliminated as possibilities for the control of extension in Punchers 1–4. Let us consider, first, τ. Given the close correspondence between τ and time-to-contact at these short intervals, it could be that the extension onsets were actually based on τ (i.e., a tau-margin strategy), but still did not yield significant time-to-contact differences. To test whether a criterial value of τ might have been used to initiate extension, we tested for differences among τs at various prior points in time. The results did not show the convincing convergence that we had observed in Figure 5, but it was the case that for both the monocular and binocular cases, Punchers 1–4 showed at least some range of intervals where no significant differences existed among τ values of the four drop types. Thus, for these 4 participants, the use of τ to initiate extension could not be ruled out. Figure 7 presents samples of these analyses. Again Puncher 5 was the exception; his extension onset could not be tied to a particular value of τ at any interval. This is consistent with our earlier claim that his flexion and extension were coupled, leaving residual flexion effects visible at "extension onset".

To determine whether other variables beside ttc and τ are still in the running for Punchers 1–4, we performed a similar analysis looking for a (new) criterial value for $\dot{r}$s to

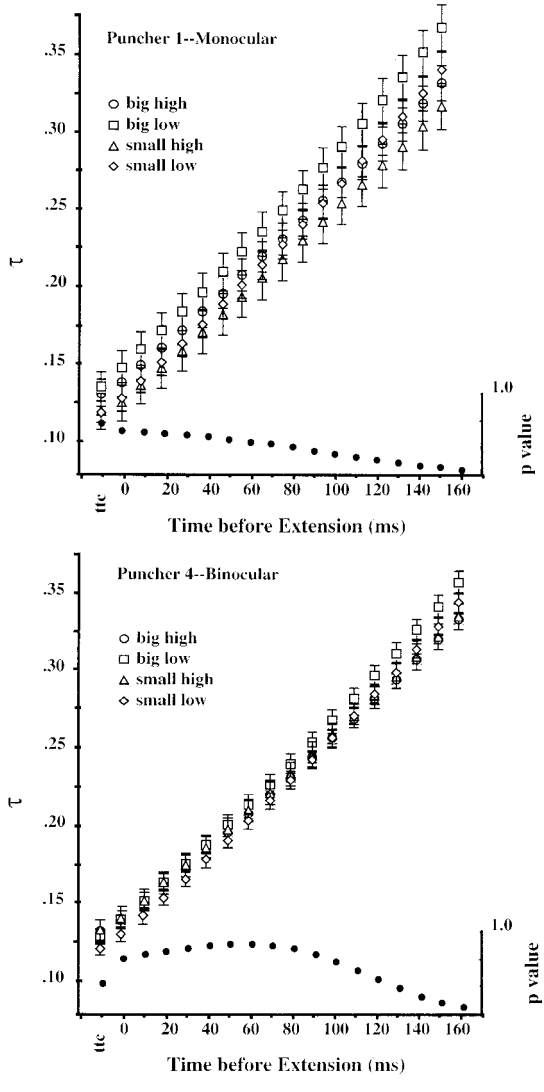

Figure 7. Average τ values and standard-error bars for the four drop types at various times prior to the onset of extension. The solid dots are *p* values for the ANOVAs testing the nulls that tau at the given interval did not differ. At the extreme left are given the averages and *p* values for time-to-contact itself, labelled ttc.

initiate extension, but the ṙs for four drop types were significantly different at all delays for all participants and conditions.

To summarize, we assume, for now, that the control of the action can be divided into flexion and extension phases, at least for Punchers 1–4, and that extension is, thereby, "initiated". If this assumption is correct, both τ and optical variables specifying time-to-contact could provide the trigger for extension, be it parameterized or not.

Extension slope. We examined peak velocity of elbow extension using ANOVAs and correlations. ANOVAs testing the effects of drop type on peak velocity within individuals found that four punchers (2–5) had height effects in the monocular condition and two (Punchers 4–5) in the binocular condition. Puncher 3 had significantly faster velocities with low balls, whereas the other punchers were significantly faster with the high balls.

To determine the possible optical bases of these effects, we computed correlations between velocity and various optical variables (r, $\dot{r}$, $\ddot{r}$, and τ) at a series of intervals prior to extension onset (0–300 ms). The highest observed correlations ranged from .257 to .629, considerably lower than those we found for average flexion velocity (Table 2). Nevertheless, the statistical significances of the ANOVAs and the correlations demonstrate that there were indeed systematic velocity differences in the extension phase of the punch. However, as with the flexion velocities, the correlations did not differ sufficiently from each other to permit firm conclusions about either variable or interval.

Summary: Individuals' joint-angle trajectories. We have considered four characteristics of joint-angle trajectories: flexion onset and velocity and extension onset and velocity. The highlights of these results are as follows: The beginning of the action occurs roughly 200–250 ms after some criterial expansion velocity, $\dot{r}$, which is very different among punchers and (sometimes) highly variable within punchers. The rate of the flexion depends on the remaining time; the shorter the time remaining the more rapid the flexion, and this effect is seen both within and between drop types. Because all optical variables are changing apace and because the punches begin at different times, we could determine neither which variable nor which interval best captured the control of flexion rate. The beginning of the extension phase is tightly coupled to the ball's imminent arrival, and the variability within drop types is equal to the variability among drop types (except for Puncher 5). Some candidate variables (r, $\dot{r}$) were statistically different just before extension initiation and thus could not be controlling it; τ and variables specifying time-to-contact, however, could not be eliminated as possible optical bases. Extension velocity showed some systematic variation, but no particular variable or interval was implicated by correlation coefficients.

In the previous analyses, both of discrete events and of discrete measures of continuous events (velocities), we have parsed the action into two phases and attempted to determine what optical variables might be involved in their onset and rates of change. This parsing is completely arbitrary. It is even possible, for example, that flexion and extension "phases" are created by one and the same (biarticular) muscle (see e.g., van Ingen Schenau, 1989). Additionally, this sort of piecemeal analysis ignores inertial effects; it looks for how the state of the system relates to optical kinematics without addressing how the state of the system relates to its prior state. In the next section we examine the punch more holistically to see if a single variable could explain the timing of the punch.

Modelling the punch

One type of model of the vertical punch would: (1) identify the relevant optics, (2) make clear the control law by which muscle activation is systematically related to the values of optical variables (and other state variables), and (3) provide the biomechanical

details whereby activation yields forces and movements. Given that a three-dimensional biomechanical model of shoulder and arm has not yet been provided by biomechanists, Step 3 must wait. If we assume that the control law relates relative torques to some optical variable and that the inertial and reactive forces are essentially the same from punch to punch, then differences in angular accelerations can be attributed to differences in the operative optical variable. We can then test the hypothesized control law and interval by seeing whether differences in optical kinematics explain the differences in the action kinematics.

We begin with an arbitrary token of the action, a time series of observed joint angles paired with time series of optical variables. The exemplar reflects the control law and mechanics at work; that is, optical variable in and movement kinematics out. Explicit hypotheses about the optical-movement interval and the control law[7] permit one to manipulate the time coordinates of the joint angles accordingly for the various drop types. For example, say that the hypothesized control law states that the observed movement begins 200 ms after $\dot{\tau}$ reaches a criterial value of 0.01 and that the movement constitutes a fixed ballistic flexion–extension. To see what collection of curves this generates, one takes the standard and aligns it such that flexion onset occurs 200 ms after $\dot{\tau}$ for the BH drop reaches 0.01. To generate the BL line, another standard is placed 200 ms after BL crosses the criterion, and so on, ending with four joint-angle trajectories. To the extent that the resulting pattern agrees with the empirical results, one may have captured the correct variable and interval. Obviously, the hypothesized control law is not a good model because it yields extension initiations that are as asynchronous as the flexion initiations.

Consider a second model that also starts with some criterial value of $\dot{\tau}$ and a ballistic flexion–extension, but where the flexion–extension is parameterized on the basis of information about time-to-contact- that the action rate is inversely proportional to the remaining time-to-contact. To see what kinds of trajectories this control law would generate, we simply choose some criterial values of $\dot{\tau}$, determine the time that each drop type would reach that value, and then compress the string of joint angles from the onset to end of action into the interval between that point and $t = 0$. To simulate this, we used the time series of average elbow angle in the monocular BH condition from Puncher 1 as the standard. The results are given in Figure 8.

Figure 8 shows a family of curves, some of which are remarkably similar to the empirical results presented in Figure 3. As in Figure 3, there are different orders of onset, different slopes, and even residual effects in the extension phase. However, as strong as is the family resemblance, this is clearly not the correct control law in that it fails to predict the small but reliable differences seen near zero in the empirical curves.

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[7] A control law, as the concept is used in ecological psychology (see Kugler & Turvey, 1987; Warren, 1988; Warren, Young, & Lee, 1986), relates information (e.g., optical or acoustical invariants) to forces. The expression of such laws could in principle take many forms. Warren et al.'s example actually relates *vertical impulse* exerted by a runner during a stride to $\Delta\tau$ (the difference between τ of the next stepping place and the one thereafter). Thus, Warren et al.'s control law relates only the time integral of forces and neglects how the forces play out over time. A fully fledged control law should capture these temporal dependencies. Second, the force in Warren et al.'s law is at the point of contact with the environment; an account of how motor elements are coordinated to create this force is also to be desired. The "control law + mechanics" we consider here also ignores the coordination of elements and the actual forces created, but does try to capture the temporal evolution of the action.

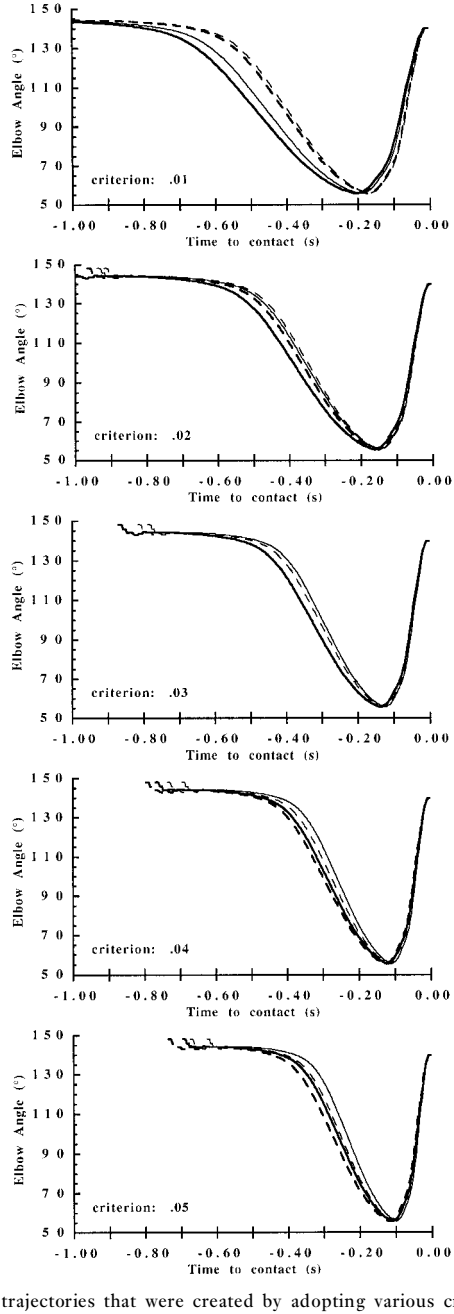

Figure 8. Simulations of trajectories that were created by adopting various criterial values of $\dot{\tau}$ (0.01, 0.02, 0.03, 0.04, and 0.05, which approximately equal the ball's optical angle in radians/s). The BH line for criterion 0.01 was taken as the standard, and the other lines were linearly compressed to the remaining time-to-contact.

What we have done in this model is to align joint angles on the time axis according to the values of optical events on that axis. An equivalent strategy is to plot the joint angles directly as a function of the optical variables and hypothesized delay (Tresilian, 1993; Wann, 1996). The goal is similar to ecological psychologists' plotting of perceived quantities as a function of information variables and seeking "single-valued functions" as indicators of the bases of perceptions (or actions). In the present case, it is not a monotonic shape that is sought, but whether drop types differ systematically in shape. Systematic differences, as in the perceptual case, indicate that the operative variable has not been found. In our next and final analysis, we explore whether the full ranges of joint-angle kinematics can be captured as single-valued functions of particular optical variables.

We have claimed that the initiation of flexion, although apparently tied to $\dot{r}$, is also variable, both between and within individuals. This means that if there exists a single-valued function even for an individual, it could only capture the curves after flexion initiation. To find whether there were such variables, we plotted the joint-angle sequences for each puncher and viewing condition as a function of various optical variables and at various intervals and looked for systematic deviations among drop types. We did this with a special eye to ensuring that scale compression did not mask systematic differences (see Wann, 1996).

The examination and comparison of literally hundreds of graphs did not reveal a variable that captured all of the joint trajectories for all of the punchers. Reasonably good fits were found for most of the results, but the lack of similarity over punchers did not inspire confidence in single-variable, single-interval control. We briefly present the findings at face value and then consider our caveats.

The binocular case of Puncher 5, to begin with, had appeared in Figure 6 to be a single-valued function of time-to-contact. There can be little doubt that in the binocular condition Puncher 5 used an optical variable that specified time-to-contact. Other variables (r and its derivatives and τ) would all yield trajectories for the four drop types that differ much more from each other (e.g., at a time-to-contact of about 500 ms, τ for high and low balls differed by about 65 ms).

The post-initiation trajectories of the other punchers' binocular conditions were best captured as changing with τ; these are presented in Figure 9. Puncher 1's binocular results are plotted as a function of τ, whereas those of the other punchers (2–4) fit better with the definite integral of $\dot{\tau}$ starting at some interval before movement onset (see legends), that is, the accumulated change in τ, rather than its current value. The elbow angle of these punchers, in other words, began to change at an arbitrary time (an average $\dot{r} \pm$error), but then changed with τ; the faster τ changed the faster elbow angle changed. Puncher 2 requires special mention: His joint-angle trajectories have been normalized. It will be recalled from Figure 6 that his movement in this condition was quite variable both in his rate of flexion and in the degree to which he flexed. The regularity in his raw joint angles emerges only in extension, which, the current analysis suggests, capitalizes on τ.

As to the monocular condition, we could not find a single variable that captured both the flexion and the extension phases for Punchers 2 and 3. In the case of Puncher 3, we believe the action was genuinely discontinuous- for the high balls, especially, he appears

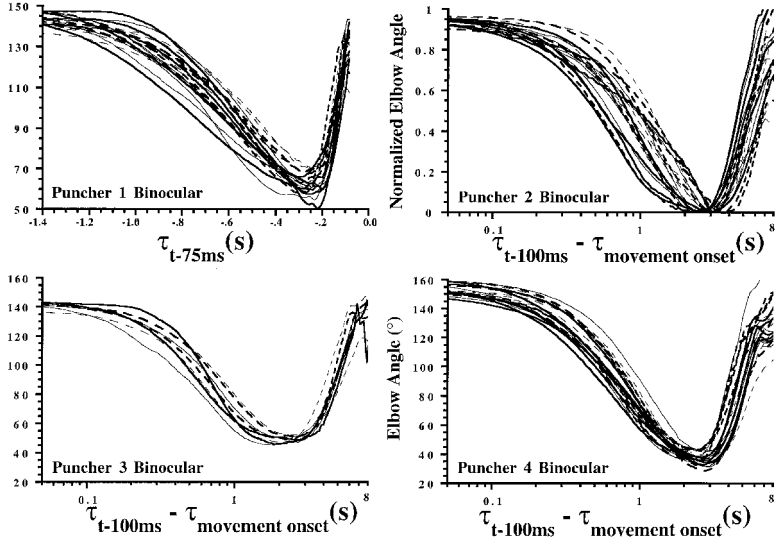

Figure 9. Continuous elbow-angle trajectories for the last 20 trials in the binocular condition plotted as a function of the best–fitting combinations of optical variable and variable-to-movement interval. Puncher 1's trajectories followed τ at an interval of 75 ms. Puncher 2's trajectories, for which the joint angles have been normalized, appeared to follow the definite integral of τ at an interval of 100 ms, as did Punchers 3 and 4.

to pause between flexion and extension; the extension portion was well captured by τ. Plots for the other three punchers are presented in Figure 10. Puncher 1 appears to follow $\dot{r}$ throughout the action; his joint-angle trajectories were best fit by the integral of $\dot{r}$ starting at movement onset. The trajectories of Punchers 4 and 5 follow the integral of $\dot{\tau}$.

What do these various fits imply? First, we emphasize that Figures 9 and 10 are not to be interpreted as definitive demonstrations of the use of particular variables. Our goal was only to ask whether there were variables and intervals that washed out the systematic differences among trajectories for the different drop types. This was the case. Additionally, it seemed that different individuals exploit different variables and that individuals use different variables in the monocular and binocular cases. We do not know whether better fits could be found using combinations of variables (Rushton & Wann, 1999) or changing intervals (cf. Footnote 4). It was the case that the operative interval for $\dot{r}$ (Figure 4) appeared to be considerably longer than the intervals estimated for τ (Figures 7 and 8).

Second, we emphasize that these fits assume that differences in kinetics are negligible, and that there is a simple relationship between differences in optical kinematics and differences in joint-angle kinematics. An alternative is a dynamic model of the sort advocated by Schöner (1994). He presented a model showing how τ might be used to stabilize and destabilize two point attractors (the initial and target postures) and a limit-cycle attractor stabilizing the trajectory. His model could easily be generalized to other optical variables, though it is less clear to us how the "target"- contacting the ball at a point of maximal fist velocity- should be expressed in attractor dynamics.

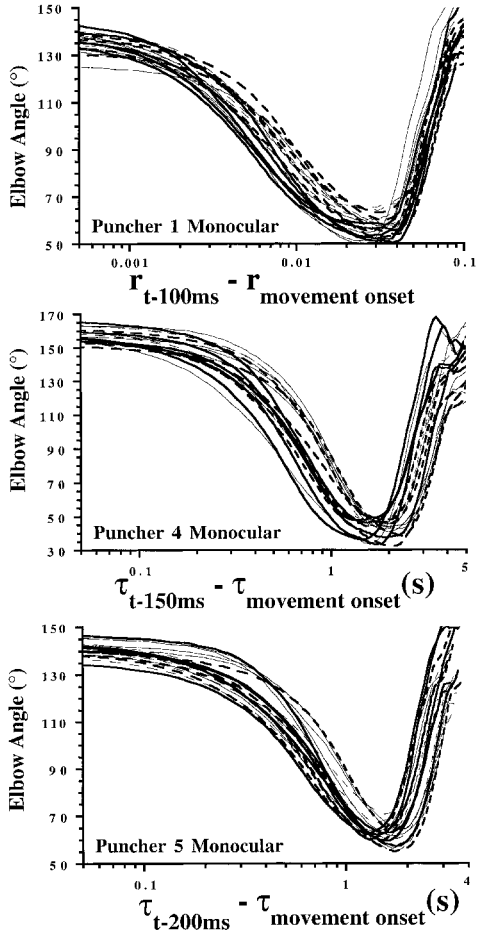

Figure 10. Continuous elbow-angle trajectories for the last 20 trials in the monocular condition plotted as a function of the best–fitting combinations of optical variable and variable-to-movement interval. Elbow angles were best fit as a function of the post-initiation integral of $\dot{r}$ in the case of Puncher 1 and of τ in the cases of Punchers 4 and 5.

SUMMARY AND CONCLUSIONS

The work of David Lee and his colleagues on τ and its role in the control of action has been an important inspiration to ecologically minded psychologists. The concept $\tau(r)$ has served as a paradigmatic example of information in the Gibsonian sense (e.g., Gibson, 1963/1982); it gave rise to a successful search for evidence of neural detection mechanisms; and it provided a platform for a host of studies that seriously addressed the interdependence of perception and action in a way that had been lacking in psychology's first century. The first round of research on τ aimed, arguably, at showing that it worked. The second round, now underway, is more sober and critical, and aims at testing whether and how τ works. Our article belongs to this second round.

We attempted to replicate important parts of the classic and influential experiment by Lee et al. (1983), while remedying what we thought were some problems and also comparing monocular and binocular viewing. We analysed a number of discrete aspects of the changing elbow angle as well as its temporal evolution. We found that individuals differ in how they execute the action- for example, protracted versus brief punches. It also appeared that punchers opportunistically exploit different informational sources to guide their action, depending on availability of information (e.g., as evidenced by differences between the monocular and binocular conditions) and depending on how they organized the action (e.g., piecemeal vs. holistically, or early starting vs. late starting).

Looming ($\dot{r}$) was implicated in the initiation of the action and, at least for one puncher, in the control of the entire action. With regard to the latter point, we can infer first from Figure 4 that $\dot{r}$ could not accurately guide the whole action if the sizes of the balls were very different. Second, it may be that one can "get away" with using $\dot{r}$ because the task does not, in fact, require precise timing. The temporal window over which one can contact the ball reasonably well is in the order of 30 ms (the time over which a ball dropped from the higher release point occupies the 0.3-m spatial window between eye level and extended fist). Given the size of the window, it may be that an approximate variable such as $\dot{r}$ can be sufficient. Timing a forehand drive in table tennis, by comparison, has only a 6.5-ms window (Bootsma & van Wieringen, 1990, see Footnote 8). A perceiver's reliance on optical variables that are "good enough", given task constraints, is a phenomenon that we have seen elsewhere (Michaels & de Vries, 1998).

In addition to $\dot{r}$, we also found that τ was implicated in the control of the action. In particular, we found that elbow angle often followed continuous changes in τ; speaking relatively among drop types, the faster τ changed, the faster elbow angle changed. The particular value of τ seemed unimportant; what was important was how $\dot{\tau}$ accumulated. Note that this is not equivalent to initiating a ballistic action based on τ, nor to a parameterization of a ballistic action based on τ, nor to any τ-margin strategy.

In sum, even though we found that τ was implicated in certain conditions for certain participants, our conclusions depart considerably from Lee et al.'s (1983) conclusions that elbow (and leg) angles were based specifically on $\tau(r)$, and, more generally, that a single variable and control law can explain both flexion and extension, both monocular and binocular viewing, and the performance of all participants. Our results suggest that some versions of τ, though not $\tau(r)$, may be implicated in extension for some individuals, whereas $\dot{r}$ seems to be the key variable in controlling flexion.

Finally, we would like to consider what the optical variables specify, or, more casually, what they are "about". One might note that a non-zero $\dot{r}$ is "about" the fact that the ball has been released, or that $\tau(r)$ is "about" time-to-contact. But, of course, it really does not matter what the variables specify as long as they are potentially useful in guiding the action. In fact, emphasizing the environmental variable that is specified invites one to think that the property as such needs to be perceived, but this puts an unnecessary perceptual entity between the information and the action: One detects $\dot{r}$, *sees that the ball is falling*, and then starts flexion; or one detects τ, *perceives imminent contact*, and then

[8] Bootsma and van Wieringen's (1990) table-tennis players could have used $\dot{r}$, rather than $\tau(r)$, as claimed. Because $\dot{r} = r/\tau(r)$, and ball size and initial distance were the same, $\dot{r}$ was proportional to τ.

starts extension. The alternative claim is that optical variables directly modulate action (e.g., Turvey & Kugler, 1984). Whereas this requires the pickup of information, it does not require the perception of the environmental event per se. Thus, using $\dot{r}$, say, to initiate flexion, would not necessarily entail perceiving ball release.

Thus, the optical variables can be said to be "about" the to-be-executed action or, less casually, as specifying aspects of the movement for an appropriately attending expert actor. The particular environmental characteristic specified by such information need not be of interest to the actor; instead, the specification relation between an optical variable and an event characteristic is a boundary condition that makes that variable potentially useful in guiding the action. We believe that this homely example- $\dot{r} > 0$ specifying the initiation of elbow flexion- makes intuitive one of the most important theses in the ecological approach, that information can specify the needed action.

The discovery of lawful relations between informational variables and the kinematics of actions leaves us puzzling less and less about how perception relates to information, and perhaps even finding it a less interesting question. Following this logic (perhaps too far), one is inclined to dispense altogether with perceptual contents. Shaw and Turvey (1981) called attention to "between-things" that stand as barriers to realism. They included sensations, features, memories, and so on, which are purported by some to mediate information and perception. The question now is whether we need perception as a between-thing that stands between the detection of information and the controlling of movement.

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Original manuscript received 30 November 1998
Accepted revision received 6 August 1999